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Strength/moisture relationship and hydraulic conductivity of Mexican tepetate

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STRENGTH/MOISTURE RELATIONSHIP AND HYDRAULIC CONDUCTIVITY

OF MEXICAN TEPETATE

by

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Tepetate is a volcanic ash-flow tuff that occurs in Mexico. Tepetate was once overlaid by a permeable soil, but has been exposed over large areas by erosion. Mexicans are forced to reclaim tepetate to improve watersheds and increase agricultural production. Strength is an important physical characteristic of tepetate and an impediment to reclamation. To ease reclamation of tepetate, data on its strength and hydraulic conductivity are needed.

Eight samples of different types of tepetate were cut into rectangular blocks and brought to various moisture contents. Unconfined compressive strength was determined on thirty-two blocks. Rates of saturated hydraulic conductivity (Ks) were also determined. Blocks were measured and weighed for bulk density, and tested for carbonate content. Strength varied from 2 kg/cm^2 under saturated conditions to 145 kg/cm^2 at oven-dry. The average rate of Ks was 8.4×10^{-5} cm/sec; this rate is classified as slow according to O'Neal (1952). Bulk density ranged from 1.2gm/cc to 2.0 gm/cc, and correlates positively with strength. Calcium carbonate ($CaCO_3$) occurred in three samples and ranged from 2 to 5%. Blocks with carbonates have higher strengths.

Tepetate strength decreases as moisture content increases, and hydraulic conductivity is slow. Bulk densities are higher than ideal arable soil (1.3 gm/cc). When $CaCO_3$ occurs, it is in similar percentage as compared to other calcic soils. Knowledge of these physical parameters can be influential in successful reclamation of tepetate.

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I doubted this day would ever come.

To all those who did not doubt, I owe a debt of thanks beyond words.

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And, finally, I dedicate my effort to the memory of my dad, who helped raise seven children and in doing so never had time to complete **his** "damned elusive thesis."

Rest in peace, Daddy. My thesis finally does.

I owe you all. Thank you from the bottom of my heart.

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"...(the) great flat-snouted and suffocating city, the city forever spreading like a creeping blot."
Carlos Fuentes

"At the least, we can be a huge warning to the world."
Anonymous city planner

ONE
Introduction

THE SETTING

Viewed from an airplane window, Mexico City seems to stretch endlessly in all directions of the compass. In 1986 (latest census year), the city was regarded as the second largest in the world; by the century's end, Mexico City is expected to be the world's largest, with a population exceeding 31 million (32). With this burgeoning population comes a need for increased agricultural production to support the city's population and maintain subsistence levels for the campesinos (farmers); this expansion will strain an already stressed ecosystem. It is doubtful whether or not any successful expansion of the agricultural system in the Valley of Mexico can be made.

Once the capital city of the Mexica (Aztec) civilization, Tenochtitlan (Mexico City) was a city of gardens and zoos and home to an estimated 500,000 people at the time of the Spanish Conquest in 1519 (12). Mexico City is in an unique geographic position to be a megalopolis, because it has natural barriers to growth. To the north, the Sierra de Pachuca; to the south, the Serrania del Ajusco.

The Sierra Nevada (Mexico's Snowy Mountains) block the east, and the Sierra de las Cruces complete the circle on the west. Because no outlet for rivers exist, Mexico City is not in a true valley, but rather a basin, or bowl. The modern city lies on a lacustrine plain--all that is left of the Aztecs' lake Texcoco--now dry, dusty...and sinking. The elevation of the plain is 2240 meters, thus the atmosphere is relatively thin; a situation exacerbated by bumper to bumper automobile traffic, industry, and an international airport.

Despite these limitations, Mexico City's population has grown six-fold since 1950; in 1986 the inhabitants numbered 18 million. With additions of 700,000 people per year (3000 per day) from outlying rural regions, and a birth rate of 2.4%, the city is easily going to meet the prediction of 31+ million by the year 2000 (32).

But where can these people live? Given the geographic limitations imposed upon them, the only place to go is, literally, up. Pushing onto mountain slopes to expand the agricultural land base is worsening an already untenable environmental situation; erosion and sedimentation have threatened agricultural activities by removing soil from the slopes and depositing it on the valley floor. And yet, campesinos have no other choice. Faced with such situations in the past, humans have not prospered; civilizations in Greece, Rome, the Near East, and Asia all have fallen victim to short-sighted agricultural practices (28). If only marginal land remains for Mexico's much-needed agricultural expansion, then reclamation is needed, and farming practices will have to improve.

Marginal land in the vicinity of Mexico City is at higher elevations. Originally, the Valley of Mexico area was settled and well-populated because of its nearness to water bordered by forests teeming with wild game. The Nahuatl (Aztec trading language) word for the valley was Anahuac ("near the water"). Over the centuries the slopes have been deforested and the soils eroded down into the valley, creating vast mudflats during the rainy season and a dusty plain in the dry season. Wind erosion contributes to air pollution by kicking up dust laden with precipitated sodium nitrate from the dry lake bed.

On the slopes erosion has exposed the subsoil, a volcanic ash flow tuff, born of volcanoes long extinct which circle the valley. The subsoil is known by the Nahuatl word construction "tepetate." "Tepetate" means "rock mat" (52), and the choice of name is obvious. Exposed tepetate looks somewhat like rock covering the ground with no plant life growing from the tepetate.

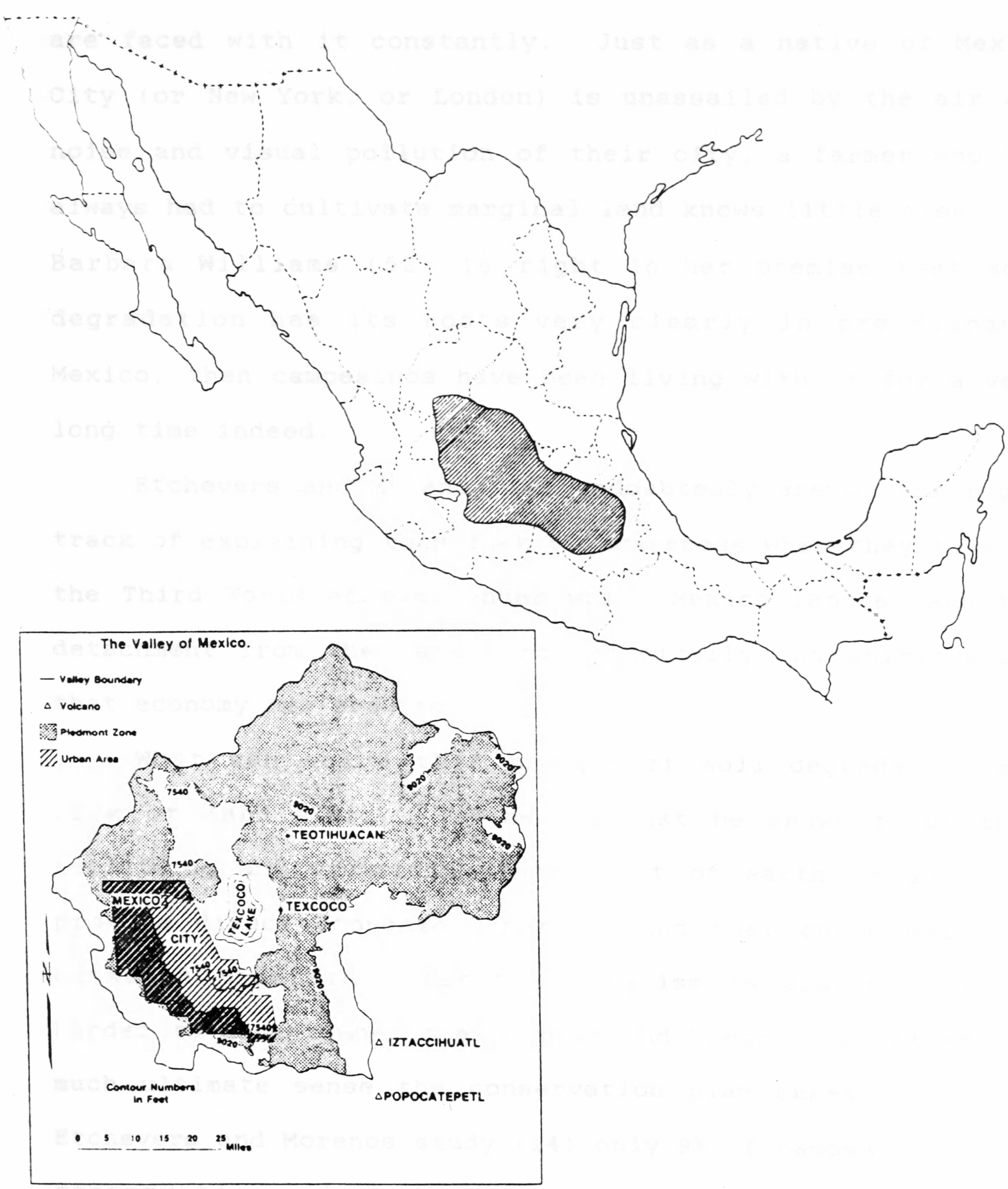
In the past, campesinos have reclaimed this subsoil on a small scale by terracing to retain water and prevent further erosion; because the area of exposed tepetate is now so great, Mexico's government is involved in reclamation, both to restore watersheds and open areas to agriculture. The Mexican government recognizes the immediacy of the erosion problem and has committed seven billion pesos (about 4.8 million United States dollars at a 1987 exchange rate of 1460 pesos to the dollar), with a further allocation of 12 billion pesos in 1988 (11). Tepetate is reclaimed by ripping it with a D-8 tractor and planting trees (mostly pine) to prevent further run-off and erosion and restore the watershed (35).

Fig. 1 (page 5) shows the approximate area of tepetate occurrence. Tepetate occurs in the neo-volcanic zone of Mexico, as indicated in the shaded area. Nimlos (34) has estimated this area to be 100,000 km^2. Exposed tepetate in the area of the Valley of Mexico (Fig. 1, insert) is found in the piedmont zone (see legend). Areas needing reclamation have been estimated at 20,000 hectares (35).

THE SITUATION

A "campesino mentality" exists that can prove to be an obstacle to planned conservation measures (11). Campesinos have a cultural attachment to the land which does not quite qualify as a land ethic insofar as Western environmentalists would define it. Etchevers and Moreno (14) conclude that a "complex interplay" of ecological, societal, economic, cultural and institutional circumstances explain campesinos who have a low awareness of degradation: they farm because

Fig. 1. Mexico: Area of neo-volcanic activity (shaded) and insert of Valley of Mexico and general study area (piedmont zone).



(From Nimlos and Ortiz, 1987.)

their family always has, and find their income from other, usually urban, vocations.

People have no awareness of degradation because they are faced with it constantly. Just as a native of Mexico City (or New York, or London) is unassailed by the air and noise and visual pollution of their city, a farmer who has always had to cultivate marginal land knows little else. If Barbara Williams (52) is right in her premise that soil degradation has its roots very clearly in pre-Hispanic Mexico, then campesinos have been living with it for a very long time indeed.

Etchevers and Moreno (14) undoubtedly are on the right track of explaining this lack of awareness when they talk of the Third World economy under which Mexico labors, and the detachment from the land, both physically and spiritually, that economy has created.

What can solve this problem of soil degradation and lack of land ethic? Campesinos must be shown first that reclaiming and stewarding their plot of earth is going to provide direct economic benefits, and that costs will not outweigh benefits. (Environmentalism is always a little harder to accept when one is poor and hungry, no matter how much ultimate sense the conservation plan makes.) In the Etchevers and Morenos study (14) only 9% of campesinos tried conservation-oriented agricultural practices. Those who did had increased production and income and lowered levels of soil loss. Yet, at least **91%** of the campesinos did **not** adopt soil conservation practices. Hansen et al. (22) agree that "appropriate" conservation measures are a must for small-scale farmers; these measures must seem economically and socially acceptable to farmers.Somehow, in some form, information that campesinos can profit from better agricultural practices must be disseminated.

THE STUDY AND ITS OBJECTIVES

Tepetate has been classified informally by 1) strength, 2) color, and 3) position of carbonates in the matrix (34, 51). Various types must be tested because of their dispersion throughout the zone of occurrence; Fincher (1988, personal communication) posits that the most common tepetate in the Valley of Mexico is that classified alternately as very strong, white, or having disseminated carbonates.

Tepetate's most important physical property, in terms of reclamation, is its strength (34). Strength of a soil means its resistance to manipulation by any force: a tractor, a hoe, or a plant root. Strength is a function of two forces in the soil matrix--cohesion between soil particles and intergranular friction (41). Tepetate is a consolidated subsoil, thus its cohesion is very high.

A common assumption is that as moisture content increases soil strength decreases (6, 23, 24, 41, et al.). However, no statistics are given by these authors to support their assumption. It is not known whether soil strength always decreases with increased moisture content, but initial studies have shown a negative correlation (36). The purpose of this study is to determine if a relationship between strength and moisture content in tepetate exists and, if so, what that relationship is.

If strength does decrease with moisture content, then to reclaim tepetate with less energy (people and machines) input, tepetate moisture content should be at its highest natural level or raised to an optimum artificial level. (An optimum level is that point at which diminishing returns would be reached; i.e. it would take more energy, time, or money to raise the moisture content further than would be saved in reclamation costs.).

Saturated hydraulic conductivity (Ks) is the rate at which a soil conducts water. Known rates are used in irrigation, stability studies, and other soil/water relationships (25). In reclaiming tepetate, knowing rates of Ks would aid engineers in artificially raising moisture contents.

As adjunct studies, bulk densities of all tepetate samples were measured, and $CaCO_3$ equivalences determined. It is hoped that this information will be of some value to those working to restore productivity to exposed tepetate subsoils.

LITERATURE REVIEW

English language articles on tepetate and its characteristics are limited. Nimlos (34, 36, 37, 38) has brought together currently available information on tepetate in an unpublished monograph. Collected there is a review of all knowledge of tepetate, both from English-language and Spanish texts. For a complete list of Spanish texts, this monograph is invaluable; many of the listings are included in Appendix C of this report. The agricultural post-graduate college at Chapingo, Mexico has many graduate theses concerning tepetate: its genesis, morphology, classification, and mineralogy. And yet there has been little study of tepetate physical characteristics other than by Nimlos (38).

General Information

There are many books on the history of Mexico. A comprehensive yet readable account of Mexico's development from 40,000 B.C. to 1986 can be found in Meyer and Sherman (32). Without a perspective on the past, one will find it difficult to prescribe for the future; past civilizations have paid dearly for a lack of understanding of previous soil management errors. Diaz del Castillo (12) wrote a fascinating account of the conquest of Mexico from his view as a conquistadore; because of its subjective perspective, it cannot be used as a guiding reference, but is highly entertaining and informative.

The origin of the name tepetate is detailed by Williams (51, 52). She traced the word construction of the Nahuatl language in order to explain her theory that land degradation had its roots in pre-Conquest Mexico. By the time the Spanish arrived, tepetate was a common glyph in Nahuatl writings; obviously the pre-Hispanics had familiarity with the exposed material. In 1450-51, unusually intense snow- and rainfalls caused devastating flooding (32); some slope denudation must have occurred to precipitate damaging flooding.

Etchevers and Moreno (14) argued that social factors are at the heart of soil degradation, and that it is more likely that inhabitants of pre-Hispanic Mexico had a conservation ethic. Modern Mexican campesinos pay a price of degraded soil in order to be close to an urban system. The authors also pointed to the connection between a Third World nation's relationship with more developed nations who demand products such as coffee, tea, sugar, and fruit, which forces landless tenant farmers off productive agricultural land. These economic conditions are a driving force behind the increased use of marginal lands for production of food (as opposed to cash, or export) crops.

Tepetate Genesis and Classification

One of the few English language reports on tepetate specifically is that of Brambila (7). He talked of tepetate as geological material which produces a soil deprived of most nutrients except potassium. He linked the hard consistency and low permeability to root growth limitations. (This limitation will be discussed later.) Brambila defined tepetate as a tuff mixture of sand, clay, and calcium carbonate ($CaCO_3$); the tepetate stratum resembles caliche with quantities of, but not dominated by, lime. Complete discussions of tuffs can be found in Ross and Smith (40). Tepetate originates in the neo-volcanic zone of Mexico (Fig. 1, shaded area); thus, most tepetate (as the word applies in the Valley of Mexico) is considered volcanic ash-flow tuff (34).

Strength

Sallberg (41) presented methodologies for three standard tests for soil strength: direct shear, triaxial compression, and unconfined compression. Unconfined compression is the quickest and most common test for cohesive soils. Specific discussions of tepetate (a cohesive subsoil) strength are available in Nimlos (34, 36, 38). He calculated correlations between bulk density and strength and concluded that bulk density is related to strength.

Strength limits reclamation activities and root growth. Most studies concentrate on the latter problem. Taylor and Gardner (45) and Taylor and Bruce (47) studied plant root growth as it pertains to soil strength, bulk density, and water content. They found that when a plant root grows down to an horizon of higher strength, the root either 1) diverts laterally, 2) grows into the horizon a short distance and then ceases elongation, or 3) elongates at a much slower rate. These reactions depend greatly on soil strength and a root's lateral support. However, availability of water and nutrients is a more influential limiting factor for root growth (9).

If tepetate strength negatively affects plant growth, strength needs to be altered through reclamation practices. Campesinos are dependent on their crops for a percentage of their food, and reclamation engineers hope to restore hydrological stability by planting trees. Decreasing tepetate strength will ease reclamation activities and improve plant growth.

Hydraulic Conductivity

Every basic text on soil moisture, soil and water, soil physics, or hydrology has a section covering hydraulic conductivity of soils (24, 6, 23, 30). Methodology for obtaining saturated hydraulic conductivity rates has been most clearly presented by Klute (25). Hewlett (23) suggested hydraulic conductivity (K) is complicated by water content variance, and recommended saturated measurements to eliminate gross variances in water content. Using either a constant or falling head of water, a soil sample is contained, saturated, and water is allowed to flow through it; outflow (Q) is captured and measured.

Saturated soils are tested for hydraulic conductivity rates for use in drainage, seepage, and structural stability studies. Unsaturated soils are tested for hydraulic conductivity rates in order to better understand infiltration, evaporation, and the flow of water to plant roots (26). Klute (25) determined that it is not necessary to perform painstaking methods of measurement for saturated or unsaturated K because of variability among samples; Hayden Ferguson, professor of soil science at the University of Montana, agrees that a rudimentary knowledge of tepetate Ks is sufficient because of the very low rates of conductivity he expected from the samples.

Klute (25) also recommends against using distilled water, and cautions that solutes will affect Ks. He advises that 1) samples be kept moist to avoid swelling of clays and slaking of aggregates, 2) samples with cracks and holes be avoided, and 3) leakage along soil and container interfaces be watched.

Calcium Carbonate in Tepetate

Tepetate in dry areas of Mexico has been found to be cemented with silica and a silica-carbonate mix (34, 35, 36, 38). An horizon cemented with carbonates is classified as a petrocalcic horizon (43) or a 'K' master horizon (17, 18, 19).

Calcic soils are defined in Soil Taxonomy (43) and the classic studies of carbonate horizon accumulation are by

Gile, Peterson, and Grossman (17, 18). They established that calcic horizon morphology occurs in four stages of carbonate accumulation for non-gravelly soils:

I - few filaments or faint coatings
II - few to common nodules
III - many nodular and internodular fillings
IV - laminar horizon overlying plugged horizon.

Machette (29) added two more stages (V and VI) for pedogenic calcrete or indurated calcic soils.

Carbonate occurrence in tepetate is depicted by Nimlos (34, 36, 38) as an accessory to silica cementation. Others spoke of tepetate as a hard calcareous derivative of limestone and travertine (10). Volcanic ash subsoils are normally carbonate-free because of the mineralogy of volcanic ash. For carbonates to be present, pedogenic development must have occurred after initial deposition (34). Machette (29) gave a possible explanation for calcareous soils in southern United States arid regions with non-calcareous parent material: $CaCO_3$ and Ca^{2+} from windblown erosion of other, calcareous soils and evaporated ocean salts in precipitation are predominant sources of carbonate accumulation in soils. Thus, tepetate is both geogenic and pedogenic, carbonate accumulation being a part of pedogenesis.

Birkeland (4) and Hanneman (21) agree that precipitation is a major source of pedogenic carbonates. Yet, precipitation rates can not be so high as to wash carbonates through the soil and subsoil profile. Tepetate with carbonates occurs where precipitation does not exceed 800mm per year (34).

"Better to let a butterfly ride the winds unnamed than to lose sight of what is truly important in our relationship to the natural world."

Stephen Whitney (1985)

TWO

Site Descriptions

Tepetate samples were collected at sites sampled earlier (36, 38). Sites were in the vicinity of Texcoco (insert, Fig. 1, page 5), and were along three transects (A, B, and C). Sampling was stratified by strength: samples selected had been shown to have varying strengths of tepetate. Strengths were categorized as high (>35 kg/cm2), medium (16-35 kg/cm2), and low (<16 kg/cm2). Broad coverage of tepetate strength ranges was desired to make the study more relevant to actual agricultural conditions. Campesinos have an informal classification of tepetate according to color; these colors (red, white, and yellow) of tepetate were collected incidentally. Data for sampling sites is given in Table 1, page 18.

Transect A contained two sampling areas: 1 and 2. Sample 1 (Fig. 2) was white and extremely difficult to remove from the profile and required a pick. Sample 2 (Fig. 3), while found off the same transect as 1, was at a higher elevation and redder in color. This sample was easily removed, although it tended to be weak and break into smaller pieces. Transect A was in an area of agricultural activity.

Fig. 2. Transect A. Note erosion and tepetate color .

Fig. 3. Transect A. Lower elevation. Note ditch depth and color of tepetate.

Sample 3 was from Transect B and from the same volcanic ash-flow as sampled earlier by Nimlos (36, 38). This sample was very light and porous, and was found in a road cut in a pine grove.

The majority of the samples (4 through 8) were collected along Transect C. Specific flows selected for sampling were vegetated with sparse stands of cactus, forbs, and grass, but had larger unvegetated areas of exposed tepetate. Sample 4 was taken from the roadcut pictured (Fig. 4).

Fig. 4. Transect C. Note roadcut exposure of tepetate and occurrence of carbonate layers.

In another roadcut, Sample 5 overlay 6 in the profile, and yet had completely different physical characteristics; 5 was white and solid, 6 was yellow and porous. Sample 7 was found in a site west of the others, where many artifacts from pre-Columbian times indicated a long-standing occupation of the land. Although it was expected to be rather strong, Sample 7 tended to crumble when removed from the ground. Sample 8 had been collected on a previous trip by Nimlos.

Table 1. Sampling Area Site Characteristics

Site	Precip.* (mm)	Elevation (m)	Slope Gradient (%)	Tepetate Color (moist)
1	762	2451	8	white
2	895	2679	3	red-brown
3	858	2615	4	yellow-brown
4	763	2454	3	red-yellow
5	763	2454	3	light grey
6	763	2454	3	brown-yellow
7	740	2414	4	olive-brown
8	665	2286	2	grey

Precipitation (*) was calculated using precipitational and elevational data from two known sites, Chapingo and Jalisco, and extrapolating to all other elevations (Nimlos, personal communication, 1988).

"...they prefer the ravings of their imagination, their gratuitous conjectures, to that laborious experience which alone can extract her secrets from Nature."

Baron d'Holbach (c. 1790)

THREE
Methodology

SAMPLE COLLECTION

Tepetate that needs reclamation is exposed to the surface in large areas; exposed tepetate was collected. To ensure that samples were as similar as possible every attempt was made to take large samples of tepetate from the same depth. ("Depth" is from the top of the exposed tepetate; it is unknown whether that "top" has actually been weathered down in some places and not in others.) Once large samples of tepetate were removed, the tops of the samples were spray-painted and placed in labelled plastic bags.

BLOCK PREPARATION

Unconfined compressive strength was tested on approximately rectangular blocks cut from the large samples with a carbide blade and hacksaw. Some samples were sanded with sandpaper of aluminum oxide with a grit of 50 or 100.

Block length was between two and three times the mean of the widths. Block width was intended to be at least three centimeters; some blocks were not that wide, although no widths were less than two centimeters. Forming the blocks to exact dimensions was very difficult in some cases. Blocks from sample 4 were most difficult because they contained coarse fragments; sand paper was useless on the coarse fragments. As a result, the desired dimensions of a length twice the width and perfectly flat tops and bottoms, which are necessary to test unconfined compressive strength, were not achieved in all cases.

BLOCK TESTING

Unconfined Compressive Strength

Unconfined compressive strength was measured at various moisture contents according to standard methods (ASTM-D-2166-66-1982) at the USDA Forest Service Materials Testing Center at Fort Missoula. Moisture contents were established at 1) oven-dry, 2) air-dry, 3) humid, and 4) saturated environments. Moisture contents varied for individual samples except those brought to oven-dry moisture content. Air-dry and saturated moisture contents had been estimated at 6% and 20%, respectively; humid moisture contents varied widely but were estimated at 12%.

Each block was oven-dried at 105 degrees C for thirty-eight hours, removed from the oven, weighed, and treated as detailed in Table 2 (page 22). After establishing moisture contents, samples were placed in separate air-tight containers.

Table 2. Establishing Moisture Contents for Tepetate Blocks

Moisture Content	Intended Moisture Content	Method of Establishment
Oven-dry	0	Placed in airtight container until tested.*
Air-dry	6	Exposed to laboratory atmosphere (17 degrees C) for 20 weeks.
Humid	12	Placed on supports in jars with water. Blocks did not touch water. Capped jars securely to ensure no air escaped. Removed and weighed periodically over eight weeks until no further weight gained showed.
Saturated	20	Immersed in water for at least 24 hours. Removed, weighed.

*Old plastic margarine and yogurt tubs were used as airtight containers. These are useful because air can be expelled easily after placing blocks inside.

Due to failure to achieve ideal block dimensions, most samples were capped top and bottom with a sulfur/sand compound according to AASHTO standards (2). These "caps" ensure a smooth plane surface to contact uniformly with the compression tester bearing plate. Sulfur "caps" dry instantaneously, and although they crumble easily, they are stronger than cement under compression, so intervening material failure determines strength. An example is pictured in Fig. 5 (page 23).

Fig. 5. Sulfur/sand compound capping top and bottom of uneven tepetate blocks.

During the sulfur-capping process, moisture gain and loss was assumed for blocks. Oven-dry blocks were tested and after 90 minutes a moisture content increase of only 0.42% on average resulted when exposed to ambient humidity. Humid and saturated blocks presumably lost moisture while being capped, but it was impossible to establish that loss. These gains and losses were not thought to affect strength or the purpose of the test significantly.

Some of the weakly cemented blocks (2, 3, 6, and 8) behaved differently when saturated (see list below).

Blocks from sample 2--slaked in most cases.

Blocks from sample 3--weakened and crumbled easily.

Blocks from sample 6--weakened and crumbled easily.

Blocks from sample 7--weakened and crumbled easily.

In these instances, a pocket penetrometer was used to determine unconfined compressive strength.

Hydraulic Conductivity

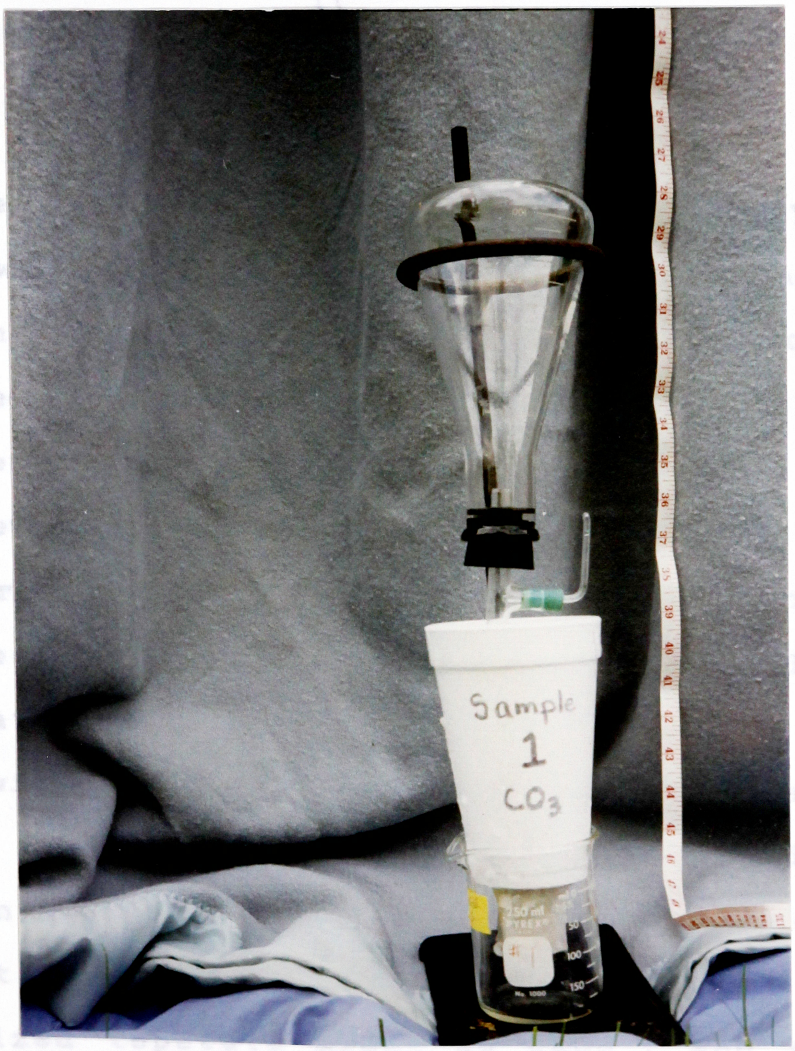
Hydraulic conductivity was determined by a method developed by Hayden Ferguson, professor of soils at Montana State University. Apparatus for this method is pictured in Fig. 6 (page 25). One block from each sample was measured for length and widths. Gulfwax brand household paraffin was melted in an empty coffee can over boiling water. One end of each block was covered with common window screen cut to size to prevent soil loss when saturated. Blocks that became weak under saturation (Samples 2, 3, 6, 7) had filter paper under the screen. Block sides were coated with viscous melted wax using a small paintbrush. (Completely melted wax was allowed to cool so when it was applied it would not penetrate the surface pores of the block.)

Wax application was repeated several times to ensure a watertight coating. Common Styrofoam cups (16 ounce capacity) were cut on the bottom to access the wax-coated blocks, one block per cup. Spaces between cup and block (both inside and out) were filled with wax and refilled until the coating was watertight.

Cupped blocks were placed on beakers of varying size (block bottom did not touch beaker bottom). Cups were filled with 14 degrees C tap water and allowed to sit at room temperature (17 degrees C) until water passed through the block (17 hours was ample time for saturation).

To maintain a constant head of water over the block, a 500ml flask was equipped as shown in Fig. 7, page 26. A stopper was pierced by a glass t-bar, converted so that one opening went through the stopper into the flask, one end was plugged with a stopper pierced by a small glass tube with a

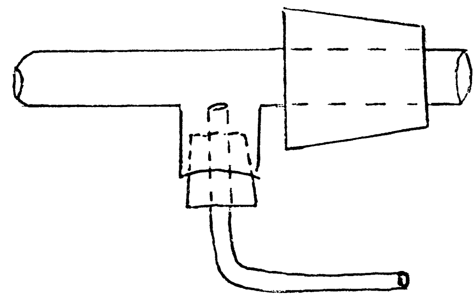
Fig. 6. Hydraulic conductivity testing apparatus.



curve, and one end had a narrowed opening which, when inverted, was below the surface of the water in the

Styrofoam cup.

Fig. 7 Modified glass T-bar for testing hydraulic conductivity.



The modified flask was inverted into the Styrofoam cups filled with water allowing passage of water; as soon as a constant head of water was obtained, the outflow was collected and measured with a 2ml graduated into 1/100ths or 5ml pipette, depending on amount of outflow.

CaCO3 Determination

Carbonate content was determined on blocks that effervesced when treated with HCl (6%). Blocks with carbonates that had been destroyed during unconfined compressive strength tests were pulverized with a mortar and pestle. Each sample was oven-dried and weighed out to 25 grams in a tared dish. (When scooping the sample into the cup, it was assumed that slightly larger pieces of pulverized tepetate might be $CaCO^3$, and these were included.) CO_3 content was determined by an acid-neutralization test (5). Solutions of 0.2547 normal NaOH and 0.54 HCl were used.

Bulk Density

Block dimensions were measured with a caliper and weighed at air-dry moisture content to determine bulk density (5).

DATA ANALYSIS

Hydraulic Conductivity

Hydraulic conductivity was calculated with the following equation:

$$Ks = (Q/At)(L/h)$$

with:
- Ks= saturated hydraulic conductivity
- Q= amount of filtrate
- A= cross-sectional area of sample
- t= time in seconds
- L= length of sample
- h= height from sample bottom to constant head.

$CaCO_3$ Content

$CaCO_3$ equivalent (%) was determined with the following equation:

$$\frac{\text{meq HCl added} - \text{meq NaOH used}}{\text{grams water-free soil}} \times 0.050 \times 100$$

(Milliequivalents were obtained by multiplying milliliters used by normality for each solution.)

"Not all those who pass/In front of the Great Mother's chair/Get passt with only a stare./Some she looks at their hands/To see what sort of savages they were."

Gary Snyder (1974)

"While we live our bodies are moving particles of the earth, joined inextricably both to the soil and to the bodies of other living creatures."

Wendell Berry (1977)

FOUR
Results and Discussion

Unconfined Compressive Strength

Block unconfined compressive strength is presented in Table 3, page 29; as moisture content increased, block strengths decreased.

Strengths obtained with a penetrometer are in bold print. The penetrometer is a vastly different technique to measure unconfined compressive strength, using a plunger with an area of about 7 mm rather than a bearing plate and compressor. Therefore, while strengths were lower, these bold-print figures should not be directly compared to higher strength results.

Replications of strength tests were run for samples 1, 2, 4, 5, and 8 under air-dry (2-4%) moisture contents. Samples 1, 2, 4, and 5 showed good duplication: the maximum variance was only 13 kg/cm^2 (Sample 4). However, the replication for Sample 8 varied by 214 kg/cm^2. An experimental error was assumed, and the higher value disregarded.

Table 3. Tepetate Strengths at Different Moisture Contents

Sample		Oven Dry	Air Dry	Humid	Saturated
1	Strength (kg/cm^2)	130	104	61	10
	Moisture (%)	0	3	8	20
2	Strength (kg/cm^2)	17	16	4	4
	Moisture (%)	0	4	12	23
3	Strength (kg/cm^2)	36	22	9	4
	Moisture (%)	0	2	9	34
4	Strength (kg/cm^2)	125	58	13	20
	Moisture (%)	0	3	14	19
5	Strength (kg/cm^2)	145	98	--	64
	Moisture (%)	0	4	19	20
6	Strength (kg/cm^2)	9	7	6	2
	Moisture (%)	0	5	24	44
7	Strength (kg/cm^2)	78	53	94	3
	Moisture (%)	0	3	9	21
8	Strength (kg/cm^2)	127	105	66	59
	Moisture (%)	0	2	5	14

Even with sulfur caps, these samples were hardly ideal for unconfined compressive strength tests. Some had cracks and other imperfections which might alter a true reading of strength.

Figures 8, 9, and 10 graph the results from the unconfined compressive strength tests. A clear relationship between strength and moisture content is apparent. As moisture content increased, strength of all tepetate samples, regardless of type, declined. Most samples' strength declined more rapidly as moisture content first increased, then leveled off. Anomalies to this pattern are samples 2, 6, and 7. Samples 2 and 6 (Fig. 9, page 31) remain stable at low strength (<20 kg/cm^2) for two or three moisture environments, then drop off. Sample 7 (Fig. 10, page 32) strength decreased dramatically at saturation. (This relationship was compromised by error in testing the humid sample.)

Sample 8 (Fig. 8, page 31) had a rapid decline of strength as moisture increased (although moisture content never gets very high), but leveled off about 63 kg/cm^2. Samples 1 and 5 were at higher moisture contents, and their strength declined almost as rapidly as 8, but continued to decline.

Figure 9 (page 31) presents non-carbonates of low strength. Again, the negative correlation between strength and moisture content is immediately apparent. All samples' strength declined as moisture content increases.

Fig. 8. Tepetate Strength/Moisture Relationship for Samples that Contain Carbonates

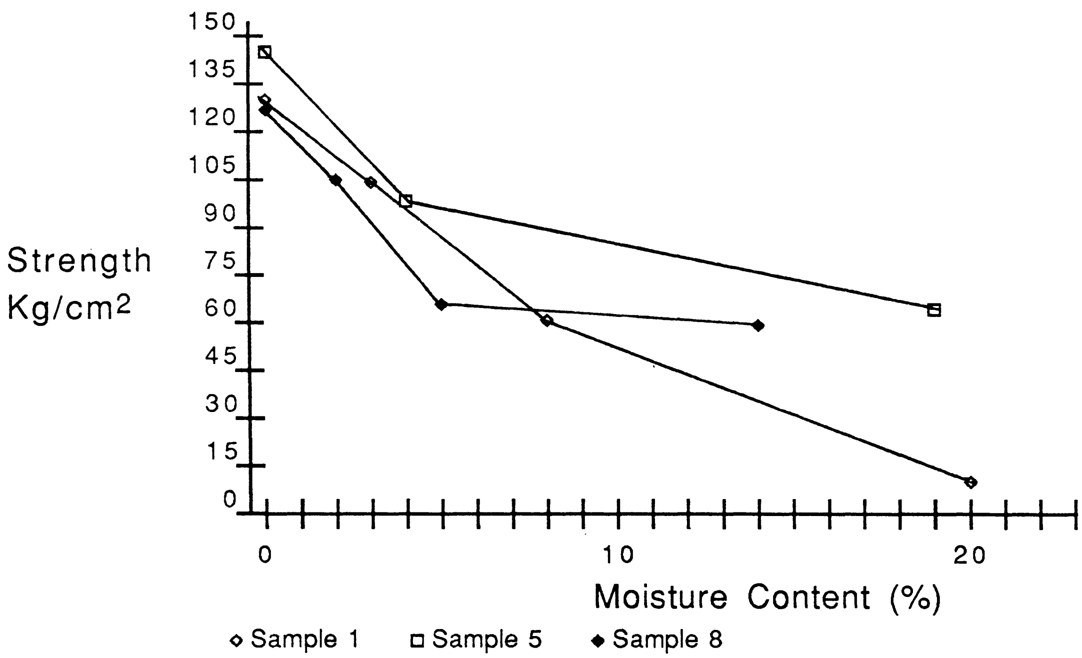
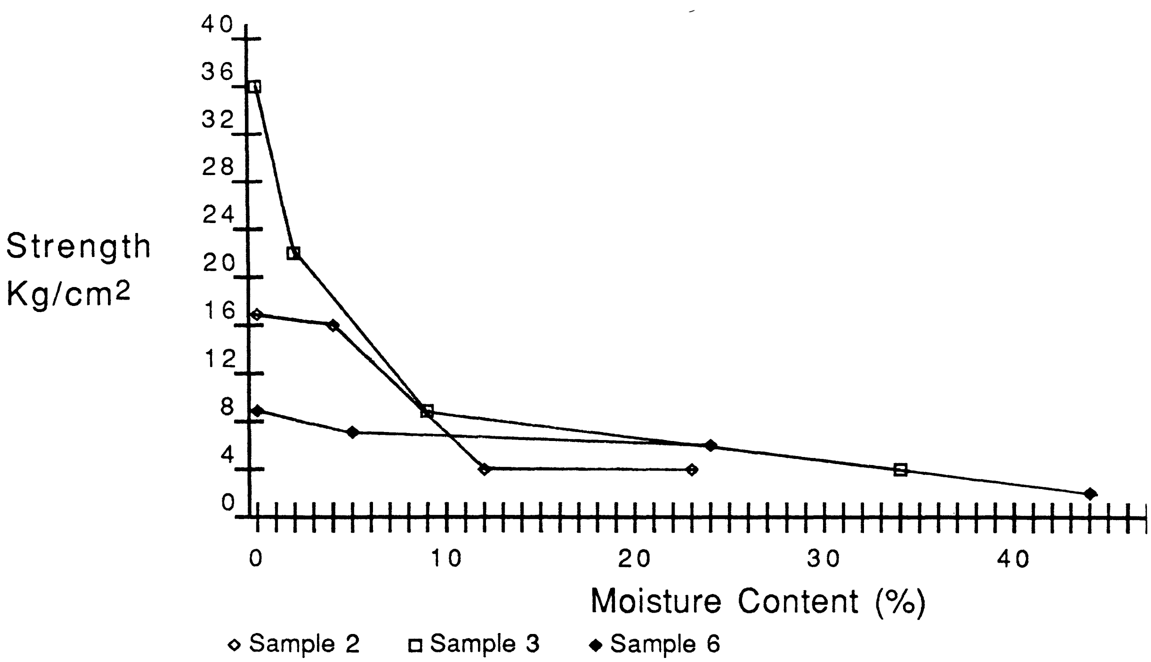
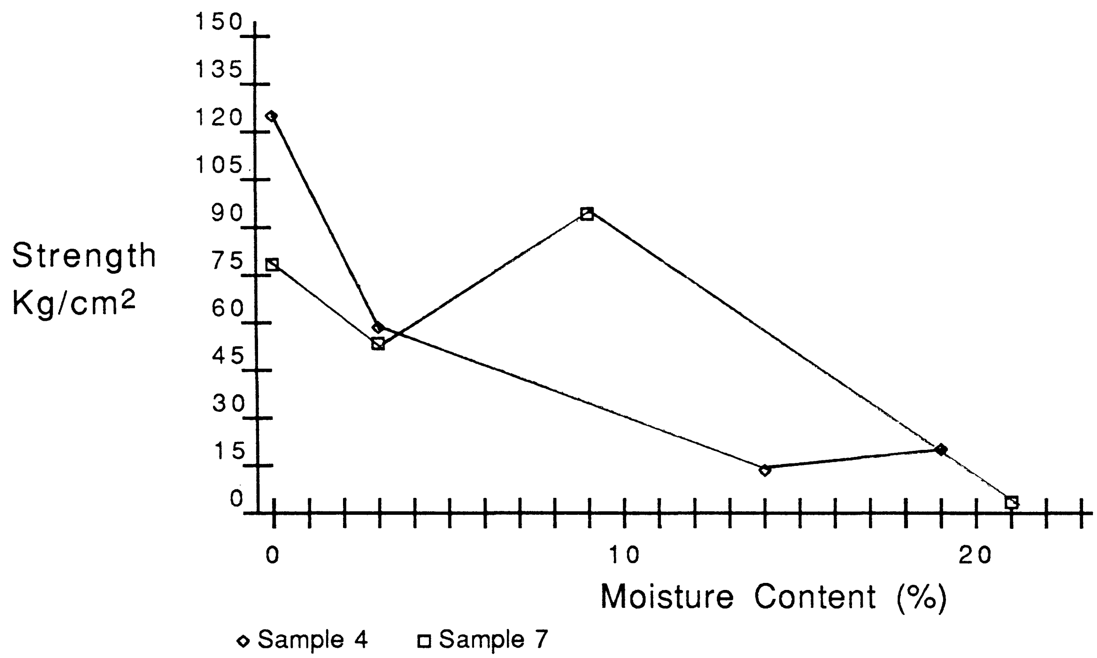


Fig. 9. Tepetate Strength/Moisture Relationship for Samples without Carbonates



Testing error is suspected for Sample 7's third test (Fig. 10). Strength reading was higher than at any other moisture content. Because the negative correlation is so pointed in all other samples, and since Sample 7 at saturation (21%) rejoins its initial trend, experimental error is assumed and the point disregarded.

Fig. 10. Strength/Moisture Relationships for Samples without Carbonates that Behaved Unexpectedly



Sample 4 has high strength readings (125 kg/cm^2 at 0% moisture) despite having no discernable carbonates (no reaction to 6% HCl was evident). However, this sample has many large (2-12 mm) coarse fragments that might influence strength when block size is quite small. Because the negative correlation was still apparent, the high strengths were not considered to be important.

Sallberg (41) lists five potential factors which can influence strength: stress history, structure, degree of disturbance, bulk density, and moisture content. In this study, moisture content was shown to have a major influence on strength. Bulk density and degree of disturbance have a lesser impact.

Degree of disturbance has a strong impact on tepetate blocks. These blocks had been cut from much larger samples, and in cases such as Sample 2, were fragile samples to begin with; as blocks they tended to crack along planes of weakness. Some samples never made it to block form. A sample taken from transect A crumbled when it was cut although in situ it had appeared to have a high strength. Sample 7 was cut with an electric saw used to prepare thin sections; 7 was saturated with diesel as a result. Samples as strong and hard as 1, 5, and 8 were little affected by any disturbance because carbonates were disseminated throughout the matrix.

According to the economic theory of diminishing returns, at some point strength decrease is less valuable than the energy input required to raise moisture contents. A valuable study needed now is how much energy is necessary per unit of moisture increase. With information about energy inputs, reclamation cost-effectiveness can be evaluated. Inflation in Mexico is at a critically high level (often in three-digit figures); twelve billion pesos allocated for 1988 soon will be reduced through attrition. Cost-effective reclamation is of paramount importance.

Calcium Carbonate

Calcium carbonate ($CaCO_3$) equivalences were run as an adjunct test; results are presented in Table 4. $CaCO_3$ had been expected to have a positive correlation to strength.

Table 4. $CaCO_3$ Concentration in Three Tepetate Samples

Sample	$CaCO_3$ equiv., % Test 1	Test 2	Mean
5	3.26	3.24	3.25
1	1.78	1.81	1.80
8	5.38	5.36	5.37

Soil Taxonomy (43) reports varying amounts of $CaCO_3$ in arid soils (Table 5).

Table 5. $CaCO_3$ Amounts and Parent Materials of Arid Soils

Soil Type	Parent Material	$CaCO_3$ Equivalent (%)
Typic Calciorthid	alluvium/rhyolite, sand, rounded gravel, andesite	2-15
Typic Camborthid	alluvium/rhyolite	<1-4
Natrargid	glacial till	<1-8

These soils are not ash-flow tuffs, as is tepetate; as stated earlier, $CaCO_3$ accumulation more often is a result of precipitation than parent material.

As suspected, samples with carbonates had significantly higher strengths compared to non-carbonate samples (Table 6). All carbonate samples had disseminated carbonates. Sample 4 had unusually high strengths for a non-carbonate, but it also had large coarse fragments throughout the matrix.

Table 6. $CaCO_3$ Concentration and Tepetate Strength

Sample	$CaCO_3$ (%)	Oven-dry Strength (kg/cm^2)	Saturated Strength (kg/cm^2)
1	1.8	130	10
2	0	17	4
3	0	36	4
4	0	125	20
5	3.25	145	64
6	0	9	2
7	0	78	3
8	5.4	127	59

Bulk Density

Imperfect block dimensions made exact length-width determinations difficult; volumes may be inexact, thus compromising bulk density measurements presented in Table 7 (page 36). A weak relationship is shown: Sample 6, with a bulk density of 1.2 gm/cc, had a correspondingly low air-dry strength (7 kg/cm^2); Sample 8 (bulk density 2.0 gm/cc) had a strength of 105 kg/cm^2 at air-dry moisture content. Too few samples were taken to plot a statistically valid graph.

Table 7. Bulk Density (Bd) and Strength of Tepetate

Sample	Bd 1 (gm/cc)	Bd 2 (gm/cc)	Bd 3 (gm/cc)	Mean Bd (gm/cc)	Strength (kg/cm^2)
1	1.64	----	----	----	104
2	1.59	1.78	1.83	1.73	16
3	1.61	1.49	1.58	1.65	22
4	1.84	1.36	1.91	1.70	58
5	1.73	1.78	1.56	1.69	64
6	1.03	1.35	1.25	1.21	7
7	1.91	1.83	1.88	1.87	53
8	2.04	1.81	1.76	1.96	105

Saturated Hydraulic Conductivity (Ks)

Rates of Ks (Table 8, page 37) are quite slow. They are ranked according to O'Neal, Table 9, page 37 (39). Smith and Browning (42) tabulated permeability classes and commented on rates and the results within subsoils (Table 10, page 38). Their rates have been converted to centimeters/second to concur with O'Neal and this study.

Each sample was tested three times without drying between testing. Replicate variation is suspected to be a result of changing the sample's Ks through continued saturation and flushing. Samples 6 and 8 had two separate samples to be tested, and their replication is quite close.

Table 8. Hydraulic Conductivity of Tepetate Samples

Sample	Test 1	Test 2 (10^{-5} cm/sec)	Test 3	Mean	O'Neal Class
1	3.8	5.0	2.0	3.6	Slow
2	2.5	4.6	3.4	3.5	Slow
3	1.9	2.9	3.3	2.7	Very Slow
4	1.0	3.2	5.4	3.2	Slow
5	28.0	18.0	62.0	36.0	Mod. Slow
6	1.3	2.0	1.7	1.7	Very Slow
7	1.4	1.6	---	1.5	Very Slow
8	23.0	13.0	10.0	15.3	Mod. Slow

Table 9. Hydraulic Conductivity Classes of O'Neal (1952)

Class	Hydraulic Conductivity (10^{-5}cm/sec)
Very Slow	<3
Slow	3-15
Moderately Slow	15-60
Moderate	60-170
Moderately Rapid	170-350
Rapid	350-700
Very Rapid	>700

Table 10. Hydraulic Conductivity Classes of Smith and Browning (1946)

Class	Hydraulic Conductivity 10^{-5} cm/sec	Comments
Extremely slow	<.07	So nearly impervious that leaching process is insignificant.
Very Slow	.07-.7	Poor drainage results in staining; too slow for artificial drainage.
Slow	.7-7	Too slow for favourable air-water relations and for deep root development.
Moderate	7-70	Adequate permeability.
Rapid	70-700	Excellent water holding relations as well as excellent permeability.
Very Rapid	>700	Associated with poor water holding conditions.

Slow rates of Ks for tepetate were not surprising; however, specific samples' rates did not meet expectations. Samples 5 and 8 had the fastest (relative) rates of Ks, and yet they are also samples with comparatively high percentages of carbonates. Carbonates mistakenly were thought to be a factor in slowing rates of Ks.

Texture is thought to have the greatest influence on Ks rates because of particle surface area and the greater attractive force of fine-textured soils (24, 25). Unfortunately, consolidated tepetate texture is difficult if not impossible to measure. To sieve tepetate samples, one would have to pulverize them. Immediately obvious is change of texture caused by the pulverization. Ultra-sound can be used to blast samples apart, but that too disturbs the natural consolidation of the tepetate. A few of the weakest samples could be saturated and allowed to crumble, and thus textures for some types of tepetate could be determined.

Other factors can influence hydraulic conductivity (24, 25). It is difficult to saturate a soil without trapping gas bubbles in pores which prevent water passage. Pore geometry, or tortuosity, also can impede water movement. Tortuosity is a description of the path water must take to flow through a soil matrix. In most cases, as the tepetate saturated it released air bubbles, which showed that its pores are not continuous. Geometry includes pore sizes; many small pores conduct less water than a few large pores.

If tepetate has clay minerals, wetting and drying it can change the structure and texture. A clay when dried can alter its texture by hardening irreversibly into a sand-sized particle (44). Clay can also intensify a cement within a soil.

Continued flushing of water through the sample may leach some compounds and cements into solution. It may explain variance of data over the testing period.

Klute (25) recommends constant-head methods for samples with fast conductivities; when hydraulic conductivity is slow, the potential for evaporation is increased. With Sample 6, after 21 hours the head had dropped significantly, but when compared to a duplicate run for a much shorter time period, rates were not too different. Most samples took one to two hours to conduct a measurable amount of water.

Leakage along sample and wax coat interfaces is a possibility, but measured rates are very slow, so it seems unlikely that leakage was occurring.

The highest rates were Samples 4 and 8. Sample 4 has many coarse fragments and frequent macropores; perhaps the coarse fragments are unable to attract water, and so conduct it through the matrix quickly. Dunn and Mehuys (13) feel methods of determining hydraulic conductivity are biased towards uniform, fine-grained samples (most hydraulic conductivity tests are run on sieved soil). Quoting Avery and Bascomb (3), Dunn and Mahuys assume any sample has to be 100 times bigger than the largest coarse fragment in the sample. This obviously would prohibit such tests. Dunn and Mahuys conclude that reduced cross-sectional areas, increased tortuosity of flow, and increased boundary flow affect rates of soil hydraulic conductivity.

While hydraulic conductivity is not permeability, it often is regarded as being the same thing; using Ks, permeability can be calculated (24). A simple conversion of rainfall intensity for an average storm (0.1 inch/hour) shows that an average intensity storm produces rainfall of 7 x 10^{-5} cm/sec; a rate just a bit faster than some tepetate samples conduct water, and slower than only two.

Tepetate has been exposed because it acted as a barrier to water flowing through the profile, and soils over tepetate were detached and flowed downhill. Yet, if tepetate conducts water at a rate only slightly slower than average rainfall intensity, there is potential for moistening tepetate and easing reclamation, if water can be held on the surface, and infiltration can be facilitated.

"A little too abstract, a little too wise,/It is time for us to kiss the earth again."

Robinson Jeffers

FIVE
Conclusion

Moisture content has been determined to weaken tepetate strength. This relationship is consistent despite the presence or lack of carbonates or coarse fragments, and across all types of tepetate. Strengths vary from 2-145 kg/cm^2, and uses of tepetate should be determined accordingly.

Saturated hydraulic conductivity of tepetate is low in most samples; the average conductivity is 8.4×10^{-5} cm/sec, which classifies as slow according to O'Neal (39). Smith and Browning (42) say this rate is too slow for favorable air-water relations or for deep root development.

Tepetate blocks with $CaCO_3$ have higher strength; bulk density also seems to have a positive correlation with strength, although there was not enough data to be certain. These parameters seem to have no influence on hydraulic conductivity.

As in any scientific study, the value and importance of these data are only equal to their applicability. Real world needs are the proper address of scientific research. This does not mean that all soil study should be edaphic. Soil has an inherent and intrinsic value, and its relationship to the human soul is worthy of pursuing. But Mexico has immediate and crucial needs to be met. Whether the ultimate goal of tepetate reclamation is to restore watersheds and protect lower elevation agriculture, or to create productive agriculture at higher elevations, any study on tepetate ideally should be of use in real life application.

Some suggestions for management can be made. Tepetate should be reclaimed when it reaches its highest natural moisture content; if timming is important, some types could be reclaimed at lower moisture contents just as economically. To raise the moisture content artificially would be costly in terms of time, energy, and water because of the slow conductivity rates. Some tepetate reclamation should be avoided: Samples 1, 5, and 8 are better used for other purposes than agricultural or hydrological.

A field guide to tepetate types is needed so identification of strengths and conductivities can be made quickly and confidently. Two aspects of tepetate that can be used to classify it in a guide or key would be color and strength.

In the end, Mexico faces a problem far more severe than erosion. If Mexico's population is not redistributed to lessen the negative environmental impacts on the Valley of Mexico, soil degradation will be a side issue to that of water shortages, toxic air pollution, and social strife caused by overcrowding. Reclaiming tepetate is important, but restructuring Mexico's population distribution is critical.

APPENDIX A
Unconfined Compressive Strength

Table 11 details the dimensions of tested blocks, and the readings of unconfined compressive strength.

Table 11. Unconfined Compressive Strength Worksheet

Sample	Cross-sectional Area (cm^2)	Length (cm)	Load (lbs)	Load (kg)	Strength (kg/cm^2)
		Oven-Dry			
1	9.07	7.14	2591	1175.28	129.58
2	10.75	6.28	408	185.07	17.22
3	13.60	7.45	1089	493.97	36.32
4	18.50	4.80	5085	2306.56	124.67
5	12.20	7.80	3895	1766.77	144.82
6	9.78	4.11	195	88.45	9.04
7	12.86	5.96	2200	997.92	77.60
8	6.20	7.84	1730	784.73	126.57
8	8.79	7.04	1044	473.56	53.87
		Air Dry			
1	10.42	8.29	2318	1051.44	100.91
1	9.87	7.94	2340	1061.42	107.54
2	16.36	9.04	622	282.14	17.25
2	9.90	6.21	313	141.98	14.34
3	13.66	7.80	673	305.27	22.35
4	13.15	7.99	1484	673.14	51.19
4	20.38	6.75	2915	1322.24	64.88
5	11.69	6.87	2620	1188.43	101.66
5	13.53	7.55	2790	1265.54	93.54
6	-----	strength undetermined			-------

7	11.87	6.13	1398	634.13	53.42
8	14.00	7.68	3255	1476.47	105.46
8	12.68	7.86	8930	4050.65	319.45
		Humid			
1	9.86	8.25	1331	603.74	61.23
2	17.09	6.98	137	62.14	3.64
3	14.80	3.02	296	134.27	9.07
4	18.48	7.66	546	247.67	13.40
5	-----	strength undetermined			-----
6	11.70	3.25	149	67.59	5.78
7	12.28	5.58	2550	1156.68	94.19
8	7.13	7.92	1032	468.12	65.66
		Saturated			
1	11.09	7.70	240	108.86	9.82
1	13.87	7.75	1817	824.19	59.42
2	10.37	6.01	167	75.75	7.30
3	-----	strength undetermined			----
4	13.99	7.42	616	279.42	19.97
5	11.49	7.22	1757	796.98	69.36
6	----	strength undetermined			----
7	----	strength undetermined			----
8	7.51	7.21	995	451.33	60.10
8	10.13	6.59	1289	584.69	57.72

APPENDIX B
Recommended Block Preparation

Block Cutting

Tepetate strength is an important parameter in reclamation. Strength is determined by compressing blocks until they rupture. Recommended methods of cutting blocks of tepetate are discussed in this appendix. Density usually is measured on the blocks also because it is another method of characterizing the tepetate.

Preliminary data (35) suggests that tepetate strength varies with sample orientation. Samples oriented vertically apparently are stronger than those of horizontal orientation. Therefore the position of blocks in the matrix must be noted. We did this by spraying the tepetate surface with paint as we removed it from the profile.

Tepetate strength is quite variable with a range of at least 2 kg/cm^2 to 145 kg/cm^2. For purposes of this recommendation we have divided tepetate into three strength classes because methods of cutting blocks into rough dimensions vary with strength.

	Kg/cm^2
Low	< 15
Medium	16-34
High	> 35

Low strength. Weakly cemented samples are difficult to collect; they tend to crumble easily when removed from the matrix and break apart when cut. However, they are so soft that they cut and sand easily; any hacksaw and blade is sufficient to cut them. Some samples are so soft that they can be cut without crumbling only when the blade is held in the hand (not attached to the hacksaw frame). Samples of this strength category should be cut extra large and sanded with great care.

Medium strength. Samples of medium strength are the easiest to prepare; most do not crumble and they can be cut in reasonable time.

High strength. Strongly cemented samples require vigorous digging with a geology hammer, pick, or bar to remove them from the matrix, and once removed, they require special cutting equipment; however, they do not crumble. Block cutting is greatly expedited when they are cut with carbide-grit blades. High tension hacksaws also expedite cutting but they are not as crucial as the carbide-grit blades. (We were unsuccessful in locating either in Mexico City.)

Blocks may also be cut with electrical hacksaws, but we found that we saved little time by using this equipment. A mechanical saw for preparation of thin sections can be used; the process is very effective on fragile samples because diesel is sprayed on the sample and saw during cutting. However, all individual samples must be treated the same, i.e. either all one sample must be diesel-saw cut, or none. This is a slow process but maintains sample integrity. A common table circular saw is very effective on samples of high strength, both for initial cutting and sanding to exact dimensions. Various blades can be used; two suggested ones are Super-disc brand from England (for sanding) and Si-clone Abrasive Blade for metal cutting by Simonds (serial number 48-60040).

There are two special problems in cutting tepetate. Stones in the matrix greatly decrease the ease of cutting and these samples should be avoided when possible. Another problem is with samples containing carbonates. If the carbonates are disseminated the samples are strongly cemented; but when the carbonates occur as laminae the tepetate shatters into aggregates easily even though the strength of the individual aggregates may be high.

Block Sanding

A variety of sandpaper is readily available for forming blocks into exact dimensions. A grit size of about 50 is best and sandpaper of aluminum oxide lasts longer than that of silicon oxide. The blocks should be placed between small blocks of wood roughly the same height and width as the desired sample size, and then sanded. Rough-cut blocks can be formed mechanically with grinders, but the dust created is harmful to the grinder. For the strongest samples, the best approach is that of the table saw with the Super-disc; it greatly accelerates the sanding process.

Blocks should be rectangular but their dimensions must be carefully controlled. The two widths of the blocks should be similar but need not be exactly the same. The length must be such that it is between two and three times the mean of the widths. Block width should be at least 3 centimeters. If possible, blocks should be as large as possible, both to guard against damage and to provide a valid unconfined compressive strength measurement. Sallberg (41) stresses the dimensions of length twice the width, but the larger the block, the better chance of a true reading of strength.

During sample preparation, large quantities of airborne particulate are created. The preparation area should be well-ventilated, and if possible a hood should be used to control dust. If these conditions are not met, the worker should wear a mask to avoid particulate inhalation.

Block Sulfur Capping

Once all blocks have been formed and sanded, one still may not have achieved perfectly flat head and base, or perfectly true right angles to the sides. In such an instance, a remedy exists. Using a sulfur-sand compound such as that marketed by Forney, samples can be capped with a substance that dries instantaneously and, although brittle, has a compressive strength stronger than that of concrete, so the intervening material determines compressive strength readings. Care must be taken to maintain verticality when dipping the block into a ring mold filled with melted sulfur, because the compound dries so quickly. The sulfur will form to the shape of the block, so the plane need not be flush to the surface of the melted sulfur. Use a smaller metal ring for the first mold so that the second mold can be pulled through the first. (This saves much time and potential breakage of blocks through stress.)

Once capped, the samples can be brought to a higher moisture content; however, they cannot be placed in an oven, as oven-dry temperatures are usually 105 degrees C, and the compound melts at 275 degrees F. If determining oven-dry strength, samples of tepetate increase in moisture content by an average of 0.46 % after 90 minutes, so moisture content is still rather low.

Sulfur-sand compound can be ordered in 50-lb. sacks from:

Forney

Route 18 Rural Delivery Number 21

Wampum, Pennsylvania, U.S.A. 16157

Telex: 81-2558

Ask for "High strength capping compound" for concrete cylinders serial #LA-0150. This compound is mixed to AASHTO specifications (2) and melted in a Forney model VRB 12 quart capacity cauldron at 275 degrees F. (These cauldrons are produced by Ogden Manufacturing Corporation.)

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